ARTICLE

Excimer laser correction of moderate to high astigmatism with a non-wavefront-guided aberration-free ablation profile: Six-month results

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PURPOSE: To evaluate the postoperative clinical outcomes and higher-order aberrations (HOAs) in eyes with astigmatism greater than 2.00 diopters (D) that had laser in situ keratomileusis (LASIK) using a non-wavefront-guided aberration-free ablation profile.

SETTINGS: Private practice.

METHODS: This retrospective study evaluated the 6-month results of LASIK for astigmatism greater than 2.00 D. Standard examinations and preoperative and postoperative wavefront analyses were performed. Aspheric treatments with a non-wavefront-guided ablation profile were planned using software integrated into the Amaris flying-spot excimer laser system, which was used to perform the ablations. The LASIK flaps were created using an LDV femtosecond laser. Clinical outcomes were predictability, refractive outcomes, safety, efficacy, and wavefront aberration.

RESULTS: At 6 months, 84% of the 50 eyes evaluated achieved 20/20 or better uncorrected distance visual acuity (UDVA) and 40% achieved 20/16 or better UDVA. Forty-four percent of eyes were within ±0.25 D of the attempted astigmatic correction, and 78% were within ±0.50 D. The mean SE was −0.12 D ± 0.25 (SD) and the mean astigmatism, 0.50 ± 0.26 D. Corrected distance visual acuity (CDVA) improved in 36% of eyes; 4% of eyes lost 1 line of CDVA. The predictability slope for astigmatism was 0.97 and the intercept, −0.15 D. There were no clinically relevant changes in any aberration metric from preoperatively to postoperatively.

CONCLUSIONS: Excimer laser LASIK using a non-wavefront-guided aberration-free ablation profile yielded excellent visual outcomes. The preoperative astigmatism was reduced to subclinical values with no clinically relevant induction of HOA.

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Excimer laser refractive surgery has evolved from simple myopic ablations[1] to sophisticated topography-guided[2] and wavefront-driven[3] procedures that use wavefront measurements of the whole eye[4] (eg, obtained using Hartmann-Shack wavefront sensors) or customized ablation patterns based on corneal topography–derived wavefront analysis.[5,6] Corneal ablations for refractive surgery treatments induce aberrations. A significant side effect of myopic laser in situ keratomileusis (LASIK) is the induction of spherical aberration,[7] which causes halos and reduced contrast sensitivity.[8] Thus, customized ablation patterns were developed to preserve the preoperative level of higher-order aberrations (HOAs).[9–11]

Several approaches to correct astigmatism have been tested, with different degrees of success.[12–17] For quasi-spherical corrections, the focus has moved from primary refractive outcomes to the effects of the ablation on postoperative HOAs; however, the main focus for astigmatism correction remains the primary refractive outcomes, principally because of problems such as coupling factors[18] and cyclotorsion errors[19] that result in residual astigmatism. In addition, the main origin of astigmatism, especially high astigmatism, is the anterior corneal surface; topographically, the main origin is usually located 2-fold symmetrically from the normal corneal vertex, not at the pupil center.

Patient satisfaction after refractive surgery, wavefront guided or not, is primarily dependent on the successful treatment of the lower-order aberrations (LOAs) (sphere and cylinder) of the eye. Achieving accurate clinical outcomes and reducing the likelihood of retreatment are major goals. Laser in situ keratomileusis has been successfully used to correct low to moderate myopic astigmatism. There is less documentation of whether LASIK is acceptably efficacious,

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predictable, and safe in correcting higher myopic astigmatism, especially with regard to the effects of astigmatic corrections on HOAs.[9,20]

We performed a study of LASIK using aberration-neutral (ie, non-wavefront-guided) ablation profiles to correct moderate to high manifest astigmatism. The non-wavefront-guided ablation profiles were optimized to preserve the preoperative wavefront aberration in the optical zone and avoid inducing aberrations, thus preventing a decrease in corrected distance visual acuity (CDVA) postoperatively (P. Artal, MD, ''What Aberration Pattern (If Any) Produces the Best Vision?'' presented at the 6th International Congress on Wavefront Sensing and Optimized Refractive Surgery, Athens, Greece, February 2005). Other ablation profiles can induce aberrations,[21] a source of which is loss of efficiency of the laser ablation due to non-normal incidence on the cornea.[22–24] We evaluated the safety, predictability, efficacy, and effect on HOAs of LASIK using the aberration-neutral profile.

PATIENTS AND METHODS

This retrospective study evaluated the first series of eyes that had LASIK for moderate to high manifest astigmatism (>2.00 diopters [D]) with an aberration-neutral profile and a flying-spot excimer laser.

Inclusion criteria were preoperative astigmatism higher than 2.00 D targeted for postoperative emmetropia, CDVA of 20/25 or better (logMAR $\leq +0.1$), a root mean square of the HOA terms of corneal wavefront aberration with a 6.0 mm diameter of less than 0.75 μm, and successful completion of a 6-month follow-up.

Preoperative and postoperative examinations included corneal topography,[25] derived corneal wavefront analysis[5] (Keratron-Scout), manifest refraction, and Snellen uncorrected distance visual acuity (UDVA) and CDVA.[26] The postoperative results reported here are from the 6-month visit. Optical errors centered on the line of sight, representing the wavefront aberration, were described by Zernike polynomials[27] and coefficients using Optical Society of America standards.[28] The corneal wavefront aberrations were analyzed for a standardized diameter of 6.0 mm.

Excimer Laser and Ablation Profile

The ablations were performed using an Amaris flying-spot excimer laser (Schwind eye-tech-solutions GmbH & Co. KG). The laser uses a real ablative spot shape (volume) calculated through a self-constructing algorithm. The flying-spot ablation pattern is randomized and controls for the local repetition rate to minimize the thermal load of the treatment.[29] The goal is a smooth ablated surface that is aberration neutral. The excimer laser has a repetition rate of 500 Hz and produces a beam size of 0.54 mm full-width-at-half-maximum with a super Gaussian ablative spot profile.[30,31] It has high-speed eye tracking (pupil and limbus tracker with cyclotorsional tracking[19]) with a 1050 Hz acquisition rate and a 3 millisecond latency time.[32]

The ablations were based on aberration-neutral profiles and calculated using the ORK-CAM software module integrated into the excimer laser. The aspheric aberration-neutral profiles are not based on the Munnerlyn formula[1]; rather, they add aspheric characteristics to balance the induction of spherical aberration[33,34]; that is, they optimize prolateness.[35,36] With these profiles, astigmatism is not corrected by superimposing the spherical component with positive or negative cylindrical patterns or by treating positive or negative cylindrical patterns based on the sign of the spherical component. Rather, the aspheric–toric volume is separated into laser pulses. The pulses are sorted spatially and temporally in a pseudorandom fashion so that the sphere and astigmatic components are not sequentially corrected but rather progressively and simultaneously corrected.

The aberration-neutral profile of the excimer laser system used in this study is aspheric based.[37] It includes a multidynamic aspheric transition zone, aberration and focus shift compensation due to tissue removal, pseudomatrix-based spot positioning, compensation for the loss of efficiency,[18] and a thermal effect control, all of which are based on theoretical equations validated with ablation models and clinical evaluations.

A 6.5 mm central fully corrected ablation zone was used in all eyes. The transition size (provided by the laser) was variable and related to the planned refractive correction (6.7 to 8.5 mm).

Ablations were centered on the corneal vertex using the pupillary offset; that is, the distance between the pupil center and the normal corneal vertex measured by videokeratoscopy (Keratron Scout topographer, Optikon 2000 SpA). The measurement was performed under photopic conditions (1500 lux), similar to the conditions under the operating microscope. This method was suggested and described by de Ortueta and Arba Mosquera[38] and comparatively tested by Arbelaez et al.[39] With the laser system used in the present study, ablation centration from the pupillary center can be modified with an offset by entering x and y Cartesian values or R and θ polar values into a regular treatment plan. The pupillary offset measurement was translated into the treatment plan as polar coordinates and then manually entered in the excimer laser computer. These optimizations theoretically diminish the induced wavefront aberration and improve the efficacy of the astigmatic correction.

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Surgical Technique

Corneal and conjunctival anesthesia comprised 2 drops of proparacaine hydrochloride 0.5% instilled 3 times before the patient was moved to the surgery area. The flap was created with an LDV femtosecond laser (Ziemer Group) with superior hinges, a 110 μm flap thickness, and a 9.0 or 9.5 mm flap diameter. A 9.0 mm marker was used to achieve centration and to allow objective measurement of the amount of applanation to ensure proper flap centration and size. Before and after the flap was lifted, online pachymetry[40] (stromal bed thickness) was performed with the integrated optical coherence pachymeter (Heidelberg Engineering). After the flap was lifted, ablation was performed, preserving the flap edges, hinge, and inner face of the flap disk. A bandage contact lens (Biomedics 55 Evolution, CooperVision, Inc.) was applied at the end of surgery in eyes with an effective flap thickness less than 110 μm.

One drop of tobramycin–dexamethasone was used 3 times a day for 1 week. Oasis extended-duration soft plugs and preservative-free artificial tear eyedrops were used for 3 months.

Outcome Measures

Refraction Spherocylindrical refraction (S, C, A) was converted to power vector notation (C_+, M, $C_\times$) using the following equations:

$$C_+ = -C\cos(2A) \tag{1}$$

$$M = S + \frac{C}{2} \tag{2}$$

$$C_\times = -C\sin(2A) \tag{3}$$

where M is the spherical equivalent (SE) power (defocus component), C_+ is the cardinal astigmatism (power of a Jackson crossed-cylinder with axes at 0 degrees and 90 degrees), and $C_\times$ is the oblique astigmatism (power of a Jackson crossed-cylinder with axes at 45 degrees and 135 degrees), S is the spherical correction of the refraction, C is the cylindrical component, and A is the angle of the neutral axis of the astigmatism.

Every dioptric power in this form can be represented by a point in Euclidean 3-dimensional space. The relationship between visual acuity and refractive power can be represented by closed surfaces of constant visual acuity in symmetric dioptric power space. The power of these 3 components can be interpreted as x, y, z coordinates of a vector representation of the power profile (ie, the **U** vector).

The **U** vector[41] can be represented as the vector in the 3-dimensional double-angle astigmatism space with $C_+/2$, M, and $C_\times/2$ as components.[42] The norm of this vector correlates to the dioptric blur and to visual acuity[43] and is calculated as

$$\|\mathbf{U}\| = \sqrt{\left(\frac{C_+}{2}\right)^2 + M^2 = \left(\frac{C_\times}{2}\right)^2} \tag{4}$$

or in spherocylindrical notation as

$$\|\mathbf{U}\| = \sqrt{S^2 + S \times C + \frac{C^2}{2}} \tag{5}$$

The mean values of these metrics, the number of eyes with postoperative astigmatism (ie, magnitude and corresponding cardinal [0/90 degrees] and oblique [45/135 degrees] components), the number of eyes within ±0.25, ±0.50, ±1.00, and ±2.00 D of the attempted astigmatic correction and of the norm of the residual **U** vector were analyzed.

Efficacy Efficacy was determined by the number and percentage of eyes with a postoperative UDVA between 20/12.5 and 20/40. The proportion of eyes at each level in that range was calculated.

Safety Safety was assessed using the difference between the postoperative CDVA and the preoperative CDVA in each eye.

Predictability Predictability was assessed using the achieved astigmatic correction (ie, vectorial difference between postoperative astigmatism and preoperative astigmatism, incorporating defocus and astigmatism) versus the attempted correction (both corrections at the corneal plane, where the ablation occurred). The magnitude and corresponding cardinal component (0/90 degrees) and oblique component (45/135 degrees) were determined. The slope and intercept of the correlations were analyzed on scatterplots.

Coupling Effect Multivariate scatterplots of the achieved defocus correction versus the attempted defocus correction and the magnitude of the attempted astigmatism correction were plotted for all eyes and for a subgroup of eyes with manifest astigmatism of 3.50 D or higher. The partial slopes and intercept of the correlation were evaluated as follows:

$$M_{Ach} = a + b \times M_{Att} + c \times C_{Att} \tag{6}$$

where M_{Ach} is the achieved defocus correction; M_{Att} is the attempted defocus correction; C_{Att} is the attempted astigmatic correction; and a, b, and c are fit parameters of the bilinear regression, with a being the intercept and b and c being the partial slopes for attempted defocus correction and attempted astigmatic correction, respectively.

If the contribution of the astigmatism to the correlation was statistically significant, the coupling factor was determined by the ratio between the partial slopes as follows:

$$CF = \frac{c}{b} \tag{7}$$

where CF is the coupling factor (ie, relative amount of achieved defocus correction per diopter of attempted astigmatic correction) and b and c are the partial slopes for attempted defocus correction and attempted astigmatic correction, respectively.

Wavefront Aberration Changes in corneal wavefront aberration were analyzed using the mean values and differences of the 30 HOA terms of the Zernike expansion to the 7th order. The postoperative values were compared with the preoperative values in each eye.

The correlations between induced aberration for each of the 30 HOA terms and the achieved refractive correction (defocus, cardinal, and oblique astigmatic components) were evaluated. The slope and intercept of the correlations were analyzed on scatterplots.

Statistical Analysis

The differences in refractive outcomes, safety, and changes in corneal wavefront aberration between

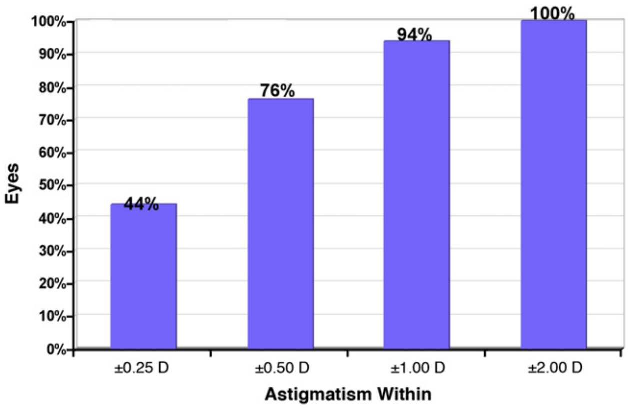

Figure 1. Astigmatism at 6 months.

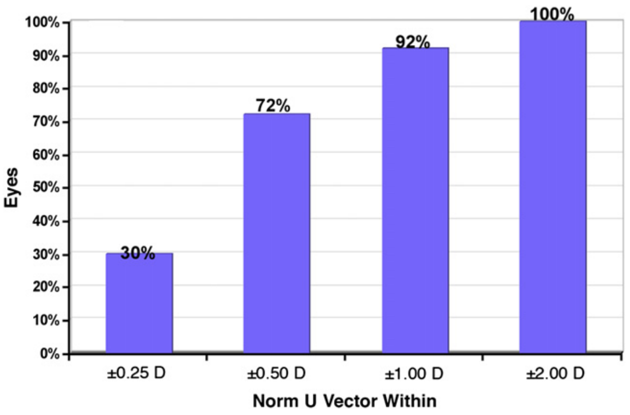

Figure 2. Norm of the **U** vector at 6 months.

preoperatively and postoperatively were evaluated using the paired Student *t* test. Predictability and the correlation between induced aberration and achieved refractive correction were assessed using the Student *t* test and the coefficient of determination (r^2); the significance of the correlations was evaluated considering a metric distributed approximately as a *t* statistic with N − 2 degrees of freedom, where N is the size of the sample. Coupling effects were assessed in the same manner but with N − 3 degrees of freedom. A *P* value less than 0.05 was considered statistically significant.

RESULTS

Fifty eyes (25 patients) were evaluated; all eyes met the inclusion criteria and completed a 6-month follow-up. Preoperatively, the mean manifest defocus refraction was −3.08 D ± 2.32 (SD) (range −7.13 to −1.00 D); the mean manifest astigmatism magnitude, 3.54 ± 0.85 D (range 2.00 to 4.75 D); the mean manifest cardinal astigmatism, 1.26 ± 3.29 D (range −3.49 to +4.60 D); the mean manifest oblique astigmatism, −0.04 ± 1.46 D (range −2.15 to +2.05 D); and the vectorial mean of the manifest astigmatism, −1.26 D at 179 degrees. No adverse events or complications were observed intraoperatively or postoperatively. No eye required retreatment.

Refraction

At 6 months, the mean residual defocus was −0.12 ± 0.25 D (range −0.75 to +0.75 D) ($P<.0001$); the mean residual astigmatism, 0.50 ± 0.26 D (range 0.00 to 1.25D) ($P<.0001$) ; the mean residual cardinal astigmatism, 0.10 ± 0.43 D (range −0.86 to +1.12D) ($P<.0001$) ; the mean residual oblique astigmatism, −0.02 ± 0.35 D (range −0.76 to +0.66 D) ($P<.0001$); and the vectorial mean of the residual astigmatism, −0.10 D at 173 degrees ($P<.0001$). Thirty-eight eyes (76%) were within ±0.50 D of the attempted astigmatic correction (Figure 1), and 46 eyes (92%) were within ±1.00 D of the norm of the residual **U** vector (Figure 2).

Efficacy

Figure 3 shows the distribution of UDVA at 6 months. The UDVA was 20/16 or better in 20 eyes (40%) and 20/25 or better in 48 eyes (96%).

Safety

Figure 4 shows the distribution of CDVA at 6 months. No eye lost more than 1 line of CDVA ($P<.01$).

Predictability

Figure 5 shows the achieved astigmatic correction versus the attempted correction at 6 months. The change in the achieved astigmatic correction was statistically significantly correlated with the intended correction (r^2 = .66, $P<.0001$). The regression slope was 0.97, close to the intended correction. The changes in achieved cardinal astigmatism and oblique astigmatism were also statistically significantly correlated with the intended correction (cardinal astigmatism: r^2 = .96, $P<.0001$; oblique astigmatism: r^2 = .86, $P<.0001$). The regression slope was 0.88 and 0.99, respectively, indicating slight undercorrection.

Coupling Effect

Multivariate correlation analysis of the achieved defocus correction versus the attempted defocus correction and the magnitude of the attempted astigmatism correction showed partial slopes of 1.01 and 0.05 for attempted defocus correction and magnitude of attempted astigmatism correction, respectively (r^2 = .90, $P<.0001$). The contribution of the attempted defocus correction was statistically significant (r^2 = .90, $P<.0001$). The contribution of the magnitude of the attempted astigmatism

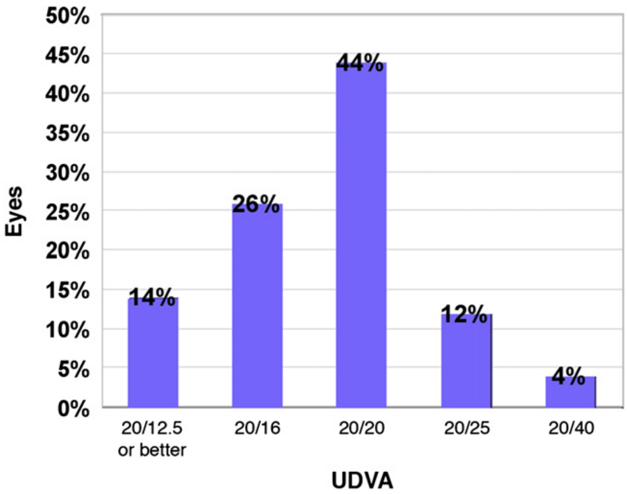

Figure 3. Efficacy: UDVA at 6 months (UDVA = uncorrected distance visual acuity).

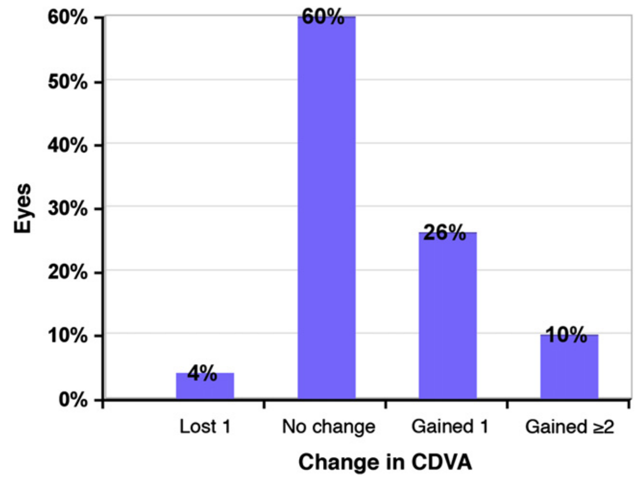

Figure 4. Safety: change in CDVA at 6 months (CDVA = corrected distance visual acuity).

correction was not statistically significant (r^2 = .01, P=.6). These findings show that there were no coupling effects of the correction of astigmatism and the correction of defocus.

Analysis of eyes with astigmatism of 3.50 D or higher (n = 14) showed partial slopes of 1.18 and 0.14 for attempted defocus correction and astigmatism correction, respectively (r^2 = .84, P<.0001). The contribution of the attempted defocus correction was statistically significant (r^2 = .84, P<.0001), and the contribution of the magnitude of the attempted astigmatism correction was not (r^2 = .11, P = .3); thus, there were no coupling effects from the correction of the astigmatism in the correction of defocus after LASIK for astigmatism of 3.50 D or higher.

Changes in Corneal Wavefront Aberration

Five of 30 higher-order Zernike terms changed significantly after treatment (Table 1). The variations were well below clinical relevance for all 30 Zernike terms.

Correlation: Induced Corneal Wavefront Aberration and Refractive Correction

For 7 higher-order Zernike terms, the induced aberration was statistically significantly correlated with LOA correction (Table 2). For 3 Zernike terms, the induced aberration was significantly correlated with the defocus correction; for 5 terms, with the correction of cardinal astigmatism; and for 2 terms, with the correction of oblique astigmatism. In all cases, the induced aberration was well below clinical relevance. The most dominant induced HOA correlations were C(4,0) and C(6,0) versus defocus correction, C(4,+2) (secondary cardinal astigmatism) versus (primary) cardinal astigmatism correction, and C(4,−2) (secondary oblique astigmatism) versus (primary) oblique astigmatism correction (Figure 6).

DISCUSSION

The aim of this study was to evaluate the results of treating moderate to high astigmatism with a flying-spot excimer laser and a non-wavefront-guided (aberration neutral) ablation profile. The goal of this ablation profile is to leave the preoperative HOA unchanged, thus maintaining preoperative CDVA and contrast sensitivity. In our study, the increase in corneal aberrations with a 6.0 mm pupil was minor.

Several techniques and ablation profiles to correct astigmatism have been used. Although many studies report good results for the correction of compound myopic astigmatism by photorefractive keratectomy (PRK) and LASIK, the ablation profiles usually cause a hyperopic shift because of the coupling effect in the flattest corneal meridian. Likely mechanisms of the coupling effect are epithelial remodeling and factors such as smoothing by the LASIK flap.[44] In eyes with a large amount of preoperative astigmatism, deviations from the target refraction are usually attributed to coupling factors. Nevertheless, assessing the coupling factor is difficult because it seems to be dependent on many things; for example, differences between excimer laser systems, flap cutting that alters the initial refraction, and preoperative corneal curvature.

Over a 6-month follow-up, no eye required retreatment, even though no nomogram adjustments were made. To confirm stability of the treatment, longer follow-up of a larger number of eyes is required.

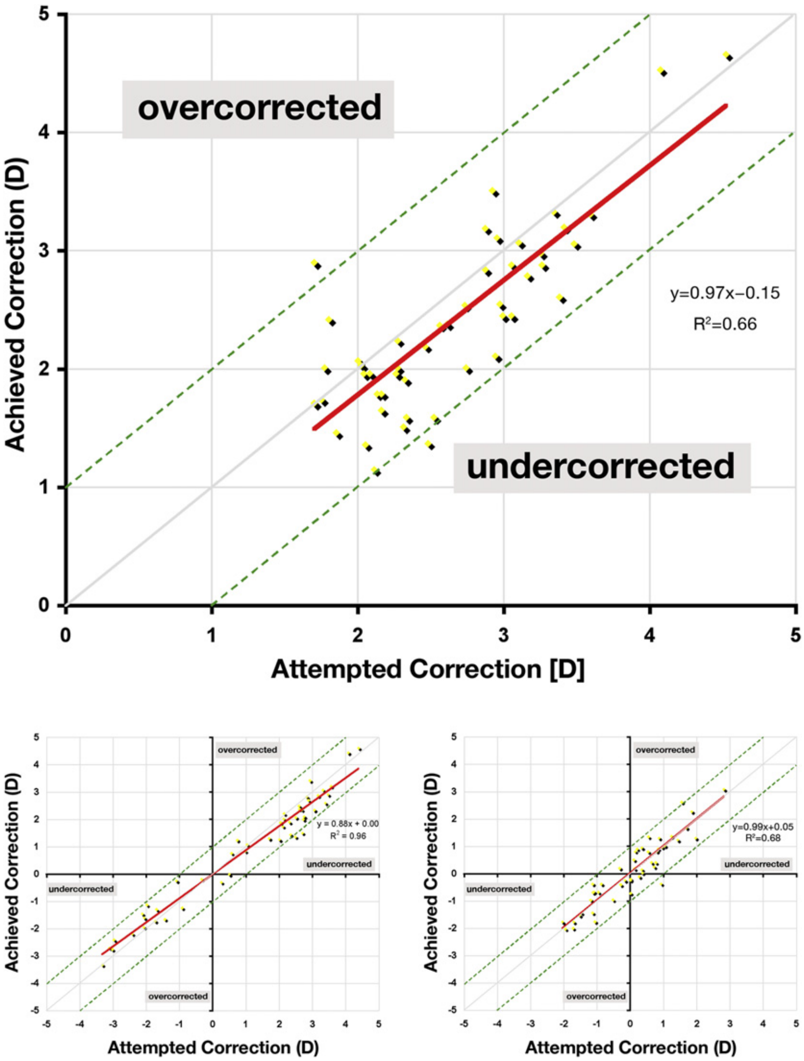

Figure 5. Achieved correction versus attempted correction at 6 months. *Top*: Magnitude. *Bottom left*: Cardinal component. *Bottom right*: Oblique component.

In our study, the mean residual defocus was approximately −0.100 D and the residual cylinder, approximately 0.500 D. More than 72% of eyes were within ±0.50 D of the target defocus and astigmatic correction, and more than 92% were within ±1.00 D. The mean decrease in astigmatism magnitude was 93%, which indicates slight undercorrection of the preoperative astigmatism. The mean postoperative defocus component showed no hyperopic shift, even though we did not make nomogram adjustments or account for coupling effects.

Multivariate correlation analysis of the achieved defocus correction versus the attempted defocus correction and the magnitude of the attempted astigmatism correction showed that the contribution of the magnitude of the attempted astigmatic correction was not statistically significant (all eyes, $r^2 = .01$, $P = .6$; eyes with ≥3.50 D astigmatism, $r^2 = .11$, $P = .3$); therefore, the astigmatic correction had no coupling effect with defocus correction. Even if the lack of statistical significance were due to the limited number of eyes (n = 50; 14 with astigmatism ≥3.50 D), the magnitude of the potential coupling factor would be less than 5% (12% for astigmatism ≥3.50 D), well below other reported values.[15,45]

In our study, all eyes had a 6-month postoperative UDVA of 20/32 or better and 84% had a UDVA of 20/20 or better. No eye lost more than 1 line of CDVA; 5 eyes gained 2 or more lines ($P < .01$).

Kremer et al.[46] evaluated the efficacy of PRK to correct high, moderate, or low astigmatism in 92 eyes. At 12 months, the mean reduction in preoperative refractive cylinder was 81%, 68%, and 48% in the high, moderate, and low astigmatism groups, respectively. Hamberg-Nyström et al.[47] evaluated more than 100 eyes treated with photoastigmatic keratectomy (PARK). Astigmatism was reduced by 44% in the low astigmatism group (<2.00 D) and by 72% in the high astigmatism group (≥2.00 D). Zadok et al.[48]

Table 1. Comparison of preoperative and postoperative corneal HOAs (6.0 mm diameter).

	Corneal HOA (μm)		
Zernike Term	Preoperative	Postoperative	*P* Value
C(3,−3)	−0.14	−0.02	<.0001
C(4,+2)	−0.08	−0.14	<.005
C(4,+4)	+0.03	+0.01	<.05
C(5,−3)	+0.01	−0.01	<.0001
C(6,0)	0.00	+0.03	<.0001
HOA RMS	+0.47	+0.57	<.0005

HOA = higher-order aberration; RMS = root mean square

Table 2. Correlations of induced corneal HOAs after LASIK (6.0 mm diameter).

Zernike Term	Slope (μm/D)	Intercept (μm)	*P* Value
Correlated to defocus correction			
C(4,0)	−0.05	−0.06	<.0005
C(4,+2)	+0.01	+0.01	<.005
C(6,0)	−0.01	0.00	<.0001
Correlated to cardinal astigmatism correction			
C(3,−3)	−0.01	−0.07	<.05
C(4,+2)	−0.09	0.00	<.0001
C(4,+4)	−0.01	+0.01	<.05
C(6,0)	+0.01	−0.01	<.0001
C(6,+2)	−0.01	0.00	<.005
Correlated to oblique astigmatism correction			
C(4,−2)	−0.09	−0.01	<.0001
C(6,−2)	−0.01	0.00	<.05

evaluated the efficacy of PARK in more than 100 eyes. The mean reduction in cylindrical correction was 84% in the low astigmatism group, 91% in the moderate astigmatism group, and 75% in the high astigmatism group.

Brodovsky et al.[49] evaluated the accuracy of excimer laser correction of myopic astigmatism by multipass/multizone PARK in a consecutive series of 332 eyes with low or high myopic astigmatism. They found a mean astigmatic correction of 89% and 98% in the low myopic astigmatism group and high myopic astigmatism group, respectively. Colin et al.[50] evaluated the precision, accuracy, and safety of 3 modes of excimer laser surgery for myopic astigmatism in 150 eyes with compound myopic astigmatism. At 12 months, the cylinder was reduced by 51%, 72%, and 36%, respectively (per mode), in eyes with low astigmatism and by 70%, 78%, and 46%, respectively, in eyes with high astigmatism. Eggink et al.[51] compared the efficacy, safety, and stability of PARK in 41 eyes with myopic astigmatism. They evaluated eyes with a high preoperative SE subjective manifest refraction (>6.00 D) and eyes with a low preoperative SE subjective manifest refraction (≤6.00 D) as well as eyes with a high preoperative cylindrical component (>2.00 D) and eyes with a low preoperative cylindrical component (≤2.00 D). Twelve months after surgery, the mean reduction in the astigmatic component was 67%.

The mean decrease in astigmatism magnitude of 93% in our study compares favorably with findings in previous studies, which report a mean decrease ranging from 36% to 91%. Barraquer and Gutiérrez[14] evaluated the efficacy and safety of steepening the flatter meridian with LASIK to correct the hyperopic compound astigmatism in 111 eyes. At 6 months, the mean residual cylinder was −0.61 D. In a study by Eggink et al.,[51] the postoperative mean cylinder component was 0.60 ± 0.70 D. Payvar and Hashemi[52] studied the efficacy, predictability, and safety of LASIK for moderate to high simple or compound myopic astigmatism in 92 eyes. Six months after LASIK, the mean astigmatism was 0.32 D at 7 degrees. We found a residual cylinder of approximately 0.5 D (or −0.10 D at 173 degrees), which compares favorably with results in previous studies.

In the study by Kremer et al.,[46] 89% of eyes with low cylinder, 82% of eyes with moderate cylinder, and 85% of eyes with high cylinder achieved a final UDVA of better than 20/32 at 12 months. In the study by Hamberg-Nyström et al.,[47] 80% of eyes with low astigmatism and 90% of eyes with high astigmatism achieved a UDVA of 20/40 (0.50) or better. In the study by Zadok et al.,[48] 84% of eyes achieved a UDVA of 20/40 or better. In the study by Eggink et al.,[51] 71% of eyes achieved a UDVA of 0.8 or better.

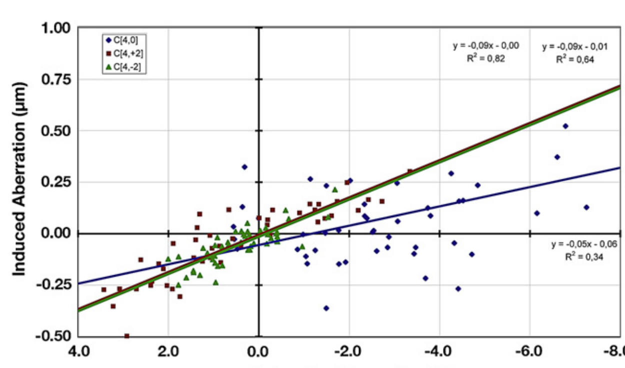

Figure 6. Change in corneal aberrations with a 6.0 mm diameter at 6 months for spherical aberration C(4,0) versus defocus correction, secondary cardinal astigmatism C(4,+2) versus primary cardinal astigmatism correction, and secondary oblique astigmatism C(4,−2) versus primary oblique astigmatism correction.

In the study by Barraquer and Gutiérrez,[14] 71% of eyes had a UDVA of 0.50 or better 6 months postoperatively. In the study by Payvar and Hahemi,[52] 80% of eyes had a UDVA of 20/40 or better. In our study, all eyes achieved a UDVA of 20/32 or better.

In our study, femtosecond LASIK performed with the combined LDV and Amaris platforms in eyes with moderate to high astigmatism was safe and effective. This is an improvement over previous laser platforms. The improvement may be because the high-speed excimer laser system reduces variability from stromal hydration effects, which increase with time of treatment.[53,54] We did not evaluate the effect of defocus and astigmatism on postoperative night-vision complaints; an analysis of this would be of interest. Further analysis of the data according to optical zone size would also of interest. Long-term follow-up of the eyes in our study will help determine whether the accurate results show improved stability over that in previous studies.

Despite large defocus and astigmatism magnitudes, HOAs were minimally increased or unchanged after surgery with the combined femtosecond–excimer laser system we used. The most significant correlations of induced HOAs were for C(4,0) and C(6,0) versus defocus correction, for C(4,+2) versus cardinal astigmatism correction, and C(4,−2) versus oblique astigmatism correction. The refractive results in this clinical setting show a trend toward slight undercorrection of astigmatism. On the other hand, the low standard deviation and the tight dispersion of the cluster of data show the consistency of the achieved results. Given the small deviation in the refractive results, we believe that with slight adjustment for astigmatic correction, the percentage of eyes within ±0.50 D of the intended correction will increase significantly. The same applies to the difference in the rate of aberration induction between defocus correction and astigmatic correction, with the latter being approximately twice as large as the former. Induced corneal spherical aberration was correlated with achieved defocus correction ($P<.0001$); it increased on average by 0.05 μm per diopter of achieved defocus correction with a 6.0 mm analysis diameter. Induced corneal secondary astigmatism aberration C(4,±2) was correlated with astigmatic correction (cardinal and oblique) ($P<.0001$); it increased on average by 0.09 μm per diopter of achieved astigmatic correction.

None of the coma aberration terms—that is, C(n,±1)—changed significantly after treatment, nor was coma induction correlated with the correction of LOAs. Although we did not specifically evaluate ablation centration by the laser, our findings on the induction of coma aberration terms indicate that the centration was accurate.

The main postoperative HOA effects (coma and spherical aberration) result from decentration and edge effects and the large change in curvature from optical zone to transition zone and from transition zone to nontreated cornea. Thus, it is important to use very large optical zones to cover the scotopic pupil size and provide tolerance for possible decentrations and to use well-defined, smooth transition zones. In our study, we used a 6.5 mm diameter, fully corrected ablation zone with a multidynamic aspheric transition zone (6.7 to 8.5 mm diameter) that the laser automatically provides based on the planned refractive correction.

The astigmatic correction was good, with no difference between lower and higher corrections. Although this small series of eyes does not allow definitive conclusions or evidence-based statements, our preliminary results are promising.

We based our analysis on simple power vectors,[42] not on more comprehensive power matrices[55] that represent dioptric power in its full character. We did this because power vectors (with 3 components) are useful for adding, subtracting, and averaging powers of thin systems.

Limitations of the study include a small number of eyes, short follow-up, and lack of a control group. Despite the limitations, we show that aberration-neutral ablation profiles are better than standard ablation profiles for the correction of moderate to high astigmatism.

In summary, the combination of an aberration-neutral profile, femtosecond flap creation, and ablation by a flying-spot excimer laser yielded good visual, optical, and refractive results for the correction of moderate to high astigmatism. After LASIK, astigmatism was reduced to subclinical values with no clinically relevant induction of HOAs, which influence contrast sensitivity. Thus, aberration-neutral ablation profiles have the potential to replace currently used standard algorithms for the non-wavefront-guided correction of moderate to high astigmatism.

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